Building Research Establishment Digest

CI/SfB 1976 (D2)(F6)

DIGEST 202

June 1977

Site use of the theodolite and surveyor's level

The setting out process must provide an accurate base for the subsequent erection and assembly processes. Site staff involved in setting out should be familiar both with the potential errors attributable to the instruments they are using and the techniques required to minimise the effect of these errors. Yet, these same staff often lack any formal training in surveying methods. With their needs particularly in mind, this digest briefly describes the basic principles of the construction of the theodolite and the surveyor's level, gives details of simple checking procedures which should be carried out to ensure that an instrument is functioning correctly and recommends instrument procedures which should be adopted to control inaccuracy when setting out. It also gives simple instrument adjustments which may be carried out on site.

Some years ago the British Standards Institution started work on a Code of Practice for accuracy in building and in 1969 published Draft for Development Document PD6440 *Accuracy in Building*. The draft sets out those factors which can influence accuracy in building; it includes sections dealing specifically with the setting out process giving guidelines on how and where to use different instruments. Although when it was published there were few measurements available of the variations which occur in practice, the document recommends permissible deviations for a range of instruments which, in the opinion of the drafting committee, represent acceptable standards of workmanship and which will rarely be exceeded if good practice is followed and reasonable care is exercised.

Before this draft became a code of practice, it was thought essential that the permissible deviations should be checked as far as possible against actual measured information. The Building Research Establishment consequently undertook a project to determine the accuracy currently being achieved when setting out on building sites using a theodolite and a surveyor's level. The study was based on the use of a sample of 37 theodolites and 42 levels on 38 sites. There were 51 users* covering a broad range of skill and knowledge.

Examination of the instruments and their ancillary equipment showed them to be generally satisfactory but there were examples of bad condition and adjustment that could have led to gross errors. Tripods with loose clamping arrangements allowed significant wobble to develop. One tripod was found with a broken leg repaired with string; a theodolite which had not been checked or adjusted for five years had so much horizontal collimation error that transiting produced an error in linearity of 100 mm over 50 m. Surveyor's levels with collimation error of up to 20 mm over 50 m were recorded.

The theodolites were often capable of results superior to those achieved in practice and a significant contribution to inaccuracy was the instrument procedure adopted. The survey showed, for example, that when using a 20 sec glass arc theodolite to establish a horizontal angle, if only a single reading is taken the probable deviation has one chance in three of exceeding the permissible deviation. The accuracy achieved using a level was generally of a high standard but a few examples of excessive inaccuracy were observed. Knowledge about both permanent adjustments and instrument procedures and their combined effect on accuracy has been found lacking in those using the instruments.

***Users**

The site personnel who are currently using optical instruments to set out on a building site may be divided into three major categories: 'site engineers', 'site management' and 'craftsmen'. The category and the number employed on any site is dependent on the complexity and volume of setting out to be done.

A site engineer is usually employed where the volume of setting out is large and/or complex and cannot be undertaken on a part-time basis and without some technical expertise in the use of optical instruments. On large construction sites where the setting out cannot be carried out by one man, the work is normally divided up into a number of manageable sections each with its own site engineer who in turn reports directly to a senior site engineer.

An assistant or trainee site engineer usually performs the simpler and repetitive type of operation and reports to either a site engineer or site management.

A site agent or general foreman may carry out the preliminary setting out of a structure and then continue to use a theodolite to monitor the erection process as it proceeds. On small construction sites, where the setting out is comparatively straightforward and of short duration, he may carry out all the work himself.

Craftsmen are sometimes responsible for establishing levels in connection with their trade; for example, a foreman carpenter may use a surveyor's level to level formwork.

Prepared at Building Research Station, Garston, Watford WD2 7JR

Technical enquiries arising from this Digest should be directed to Building Research Advisory Service at the above address.

Accuracy

Tables 1 and 2 show the accuracy that can be expected using theodolites and surveyor's levels. The figures are based on PD6440, modified where necessary in the light of the BRE survey and other recent information.

The permissible deviations are those which may occur but will rarely be exceeded if good practice is followed and reasonable care is exercised.

Table 1 Permissible deviations using the theodolite

Instrument	Permissible deviation	Comments
Setting out and measurement of angles		
Vernier theodolite graduated to 20 sec.	± 40 sec. (± 10 mm in 50 m)	Mean of two sights one on each face. For horizontal angles readings to be taken in opposite quadrants of the horizontal circle.
Glass arc theodolite graduated to 20 sec.	± 20 sec. (± 5 mm in 50 m)	Scale readings estimated to the nearest 5 sec. Mean of two sights one on each face. For horizontal angles readings to be taken in opposite quadrants of the horizontal circle.
Glass arc theodolite graduated to 1 sec.	± 5 sec. (± 2 mm in 80 m)	Mean of two sights one on each face
Establishing verticality		
Glass arc theodolite graduated to 20 sec. and diagonal eyepiece	± 5 mm in 50 m	Mean of at least four projected points each one established at a 90° interval around the horizontal circle. Good illumination required inside buildings
Glass arc theodolite graduated to 1 sec. and diagonal eyepiece	± 5 mm in 100 m	Mean of at least four projected points each one established at a 90° interval around the horizontal circle. Good illumination required inside buildings

Table 2 Permissible deviations using the surveyor's level

Class of level	Permissible deviation	Comments
Builder's	± 5 mm per single sight of up to 60 m	
Engineer's	± 3 mm per single sight of up to 60 m ± 10 mm over 1 km	Where possible, sighting distances to be equal
Precise	± 2 mm per single sight of up to 60 m ± 5 mm over 1 km	

The accuracy in any levelling operation depends on the number of individual sightings; usually two but sometimes more. The combined error for n sightings is given by $\sqrt{ns^2}$ where s is the single sight error. For example, when using an engineer's level to establish a datum directly where neither of the two sighting distances exceeds 60 m, the permissible deviation is $\pm \sqrt{2 \times 3^2}$ mm $\simeq \pm 4$ mm.

The theodolite

Basic principles of construction

A theodolite may be regarded as a mechanical realisation of the geometry of three concurrent straight lines (Fig 1):

1 the telescope axis, ie the line of sight (line of collimation) through the telescope;
2 the transit (or trunnion) axis;
3 the standing (or vertical) axis.

The telescope axis should be perpendicular to the transit axis and the transit axis perpendicular to the standing axis. If a theodolite is in correct adjustment, once the standing axis has been set vertical, the transit axis will be horizontal and the line of sight through the telescope will sweep out a vertical plane as the telescope is elevated or depressed.

The upper part of the instrument carrying the telescope rotates about the vertical axis through the centre of a horizontal graduated circle and carries index marks to enable the horizontal angle through which the telescope has been moved to be determined. A graduated vertical circle is attached to the telescope and an index mark positioned on the main body of the instrument. With the telescope set so that the line of sight is horizontal, the instrument can be used to measure or set out vertical angles.

The accuracy specification of a theodolite is normally

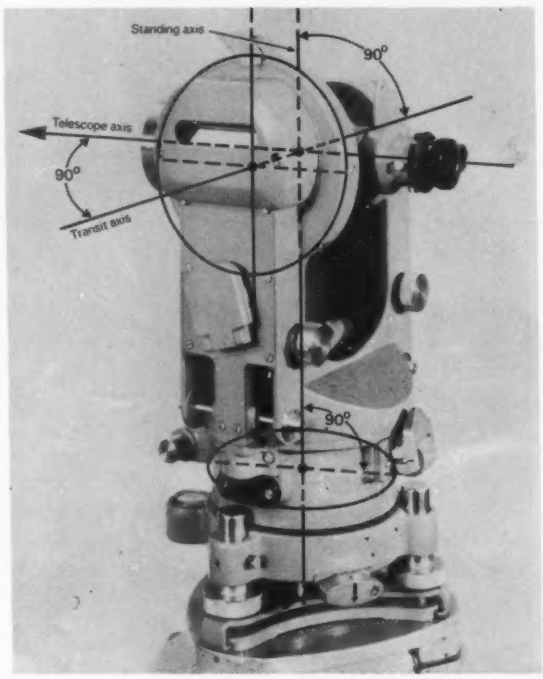

Fig 1

presented in terms of a 'direct reading specification'. This is the finest reading which can be taken directly from a graduated scale, whether this is a vernier or micrometer scale, or fixed optical scale, without sub-dividing divisions by eye. A 20-second instrument is normally adequate for the majority of setting out tasks on a building site. In exceptional circumstances, for example when setting out angles defined to single seconds or where projected sight lengths exceed about 100 m and high accuracy is demanded, it may be necessary to use a one-second instrument.

Permanent adjustments

The required relationships between the telescope axis, the transit axis and the standing axis are set by four permanent adjustments:

1 The plate bubble tube should be set so that when the bubble is in the centre of its run the standing axis is vertical;
2 The line of collimation should be set perpendicular to the transit axis (horizontal collimation).
3 The transit axis should be set perpendicular to the standing axis and therefore horizontal when the instrument is correctly set up and levelled.
4 The vertical circle index should be set so that when the telescope is adjusted to give a horizontal reading on the vertical circle, the line of sight is horizontal.

Errors resulting from maladjustment of the horizontal collimation and transit axis are cancelled out by taking observations with the vertical circle first to one side of the observer then to the other side, that is with 'face left' and with 'face right', as shown in Fig 2. The magnitude of these maladjustments should, however, be determined when an instrument first arrives on site using the techniques given in reputable surveying text-books, and if one or both are found to be unacceptable, say greater than 20 secs of arc (ie 5 mm over 50 m), the instrument should be professionally examined.

Errors resulting from maladjustment of the plate bubble tube are not automatically cancelled out by taking observations on both faces of the instrument.

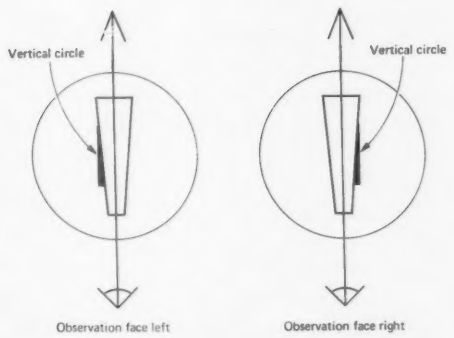

Fig 2 'Face left' and 'face right'

The recognised checking and adjustment procedures, described later, should be carried out when levelling the instrument prior to undertaking any accurate setting out. Maladjustment of the vertical circle index need only be considered when using a theodolite to measure or set out vertical angles and when optical plumbing. Although errors resulting from this will be cancelled out if observations are taken on both faces, the check and adjustment procedures are of a quick and straightforward nature and are given in manufacturers' literature and surveying text-books.

Condition of equipment

The mechanical condition of a theodolite should be examined when the instrument first arrives on site and then at regular intervals. It should be professionally overhauled at least annually if in regular use and if excessive play develops or if it has been dropped or damaged. The mechanical condition of the tripod should not be overlooked. The clamping arrangement at the tripod head and feet should be regularly checked for tightness as should the effectiveness of the leg clamp on telescopic tripods.

Control of inaccuracy in setting up

The accuracy with which a theodolite is set up will influence the accuracy subsequently achieved using the instrument. The main causes of inaccuracy are instability of the instrument and tripod, inaccurate levelling up, inaccurate centring over the station point and failure to eliminate parallax.

Instability Research has shown that the stability of the theodolite and the tripod is often overlooked. Once an instrument has been set up, a check on stability can be made by directing the telescope sights on to a mark about 50 m from the instrument and clamping the horizontal plate and vertical circle. The top of the instrument is then gently tapped sideways while observing the target with the telescope; the cross-hairs should move slightly off target and return automatically to their original position. If excessive, irregular or permanent movement is observed, the stability is suspect.

Inaccurate levelling up An instrument which is incorrectly levelled at the outset will so remain throughout that instrument position and, when the telescope is elevated or depressed, it will sweep out a plane inclined slightly to the vertical. The recognised levelling procedure outlined below should always be adopted (see Fig 3).

Lay the bubble tube parallel to two footscrews and centre the bubble with them. Move the bubble tube 90° about the standing axis and centre the bubble with the third footscrew. Check the position of the bubble with the bubble tube in the two positions as before and readjust if necessary. Move the bubble tube around the standing axis until it is parallel to and opposite its position at the outset of the levelling procedure. If the bubble remains centred then the bubble tube is correctly set. A shift in the bubble from

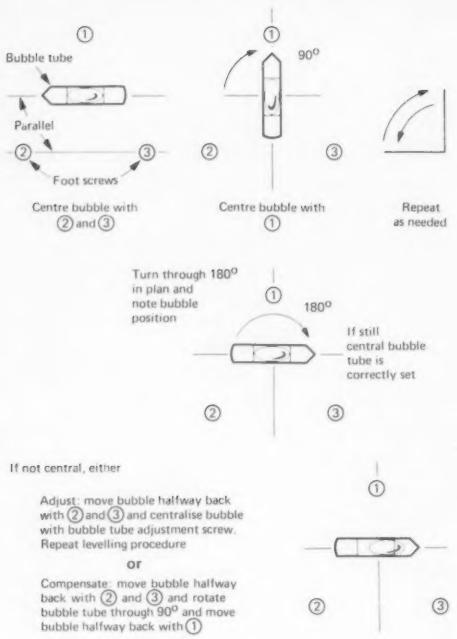
Bubble tube
Parallel
Foot screws
Centre bubble with ② and ③
90°
Centre bubble with ①
Repeat as needed
Turn through 180° in plan and note bubble position
180°
If still central bubble tube is correctly set
If not central, either
Adjust: move bubble halfway back with ② and ③ and centralise bubble with bubble tube adjustment screw. Repeat levelling procedure
or
Compensate: move bubble halfway back with ② and ③ and rotate bubble tube through 90° and move bubble halfway back with ①

Fig 3 Levelling procedure

the centre of its run denotes a maladjustment. A shift of up to one 2 mm division on the bubble tube may, for normal practical purposes, be regarded as insignificant during setting out or measurement through a vertical height of up to about 20 m. If the maladjustment exceeds this or if setting out or measurement tasks are being carried out through a greater height, it is advisable to level the instrument accurately, using the procedures outlined below. It is essential to level an instrument accurately prior to optical plumbing with a diagonal eyepiece attachment. A maladjustment can be rectified by bringing the bubble half-way back to the central position with the two associated footscrews, centring the bubble with the bubble tube adjustment screw and finally repeating the levelling procedure; alternatively it can be compensated for by adjusting the bubble with the footscrews so that no bubble movement is observed when the bubble tube is rotated about the standing axis. This is achieved by bringing the bubble half-way back towards the central position by adjusting the two associated footscrews then moving the bubble tube 90° about the standing axis and bringing the bubble once again to this mean position with the remaining footscrew.

Centring error An example of the effect of the incorrect centring of an instrument over a station point when setting out a right-angle is shown in Fig 4. The error in the position of C increases as both the centring error and the foresight distance BC increase and the backsight length AB decreases. Similarly, the error when measuring an angle increases as the centring error increases and the sight lengths decrease. As sight lengths on building sites are often comparatively short, instrument centring should be carried out as accurately as possible.

Modern theodolites are usually fitted with an optical plummet which makes it theoretically possible to centre an instrument over a point to within a fraction of a millimetre. The optical plummet is usually located in the main body of the instrument and may, unlike those fitted near the base, be rotated about the standing axis. An instrument with an optical plummet should first be approximately centred with a plumb-bob, accurately levelled with the footscrews and then accurately centred with the optical plummet. A final check on the accuracy of the levelling should then be made. The optical plummet is unlikely to be in perfect adjustment and when fitted to the main body of the instrument a check should be made to ensure that the point defined by it either remains stationary or traces out a circle centred on the station point mark when it is revolved 360° around the standing axis. If an instrument traces out a circle of unacceptable diameter (say greater than 3 mm) it should be professionally adjusted.

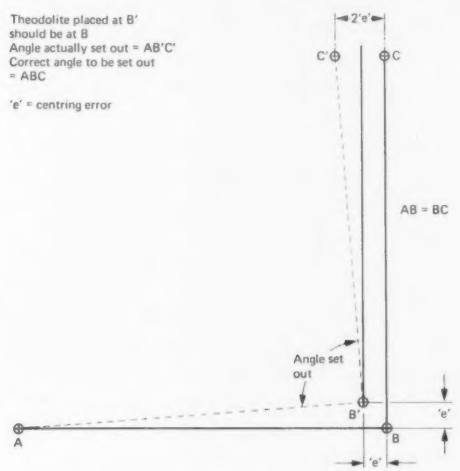

Fig 4 Inaccurate centring

Parallax error Before starting work with any surveying telescope, each observer should focus the eyepiece on the cross-hairs very carefully to eliminate parallax error due to the plane of the eyepiece image and cross-hairs not being coincident. The adjustment consists of putting the telescope out of focus, then aiming it on a light background such as the sky or a piece of paper held in front of it and, finally, slowly turning the eyepiece until the cross-hairs appear sharp and black. To check the adjustment, the observer should focus the telescope on a distant object and then move his eye up and down or from side to side. The distant object and cross-hairs should appear to be 'glued together'. If there is any relative movement the adjustment is incorrect and should be repeated.

Control of inaccuracy during setting out
Inaccuracy directly attributable to the construction and maladjustment of a theodolite is minimised if the correct instrument procedures are used. As a general rule, at least two independent measures must be taken. The following instrument procedures are recommended when extending a horizontal line by transiting the telescope, establishing plumb-lines on building elevations, optical plumbing with a diagonal eyepiece attachment, and setting out a horizontal angle.

Extending a horizontal line by transiting the telescope The extension of a straight line by setting over one end, sighting the other end and transiting the telescope is primarily subject to error from a maladjustment of the horizontal collimation. To cancel out this error, the operation must be carried out with two observations: one with face left and one with face right, and the mean of the established points is then on the correct alignment (Fig 5).

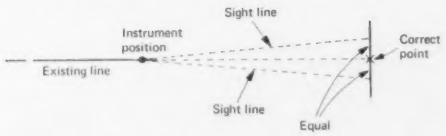

Fig 5 Extending a horizontal line

Establishing plumb-lines on building elevations Operations in which the telescope is elevated or depressed are subject to error from maladjustments of the horizontal collimation and transit axis. To cancel out these errors the telescope should always be elevated (or depressed) twice, once with face left and once with face right, and the mean of the established points accepted as being correct (Fig 6).

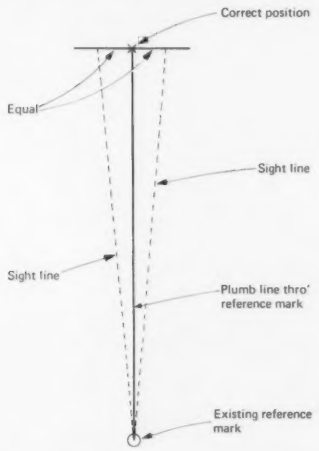

Fig 6 Establishing a plumb line

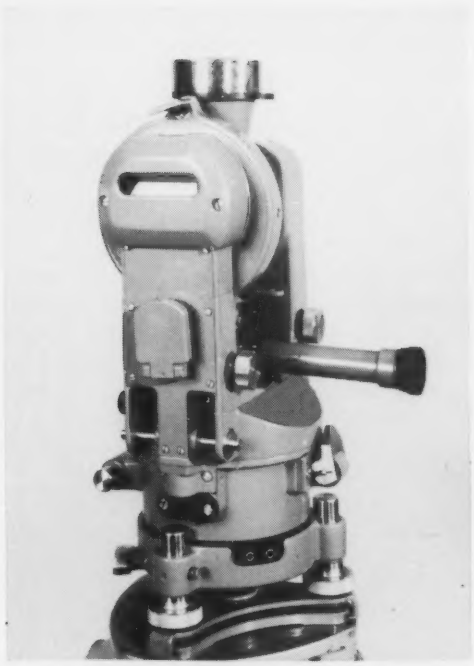

Fig 7a Theodolite with diagonal eyepiece

Optical plumbing with theodolite and diagonal eyepiece When using a theodolite with telescope set vertically and diagonal eyepiece attached (Fig 7a), a maladjustment of the horizontal collimation, the transit axis or the vertical circle index produces a line of sight which sweeps out a cone as the telescope is rotated 360° about the standing axis. To eliminate the effect of this error and the possibility of gross errors occurring, four observations should be taken at 90° intervals around the horizontal circle; the mid-points of each pair of opposite points should coincide and are then accepted as being the correct point (Fig 7b).

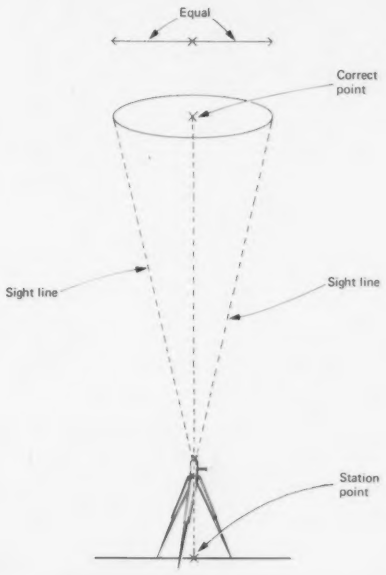

Fig 7b Optical plumbing

Setting out a horizontal angle A basic and perhaps the most common operation performed with the theodolite on building sites is the setting out of a horizontal angle of 90°. Research into the accuracy achieved by site personnel has shown that the instrument procedure has a significant influence on the accuracy achieved.

The 'simple reversal' technique Simple reversal is the basic technique which must be used to eliminate or minimise the effects of instrument errors. The technique consists of taking the mean of two positions established using both faces of the instrument and taking readings on two diametrically-opposed parts of the horizontal circle. Taking the mean of positions established by taking observations on both faces of the instrument will eliminate the effect of a maladjustment of the horizontal collimation and transit axis. Taking readings in two diametrically-opposed parts of the horizontal circle will eliminate the influence of circle eccentricity, ie when the centres of the standing axis and the horizontal circle are not coincident, and will also reduce the influence of graduation errors. Taking more than one observation will also help to identify situations in which human errors have been made.

The simple reversal technique when setting out an angle is illustrated in Fig 8. The example is based on the common angle of 90° when set out in a clockwise direction but the procedure is exactly the same for any angle set out in either direction.

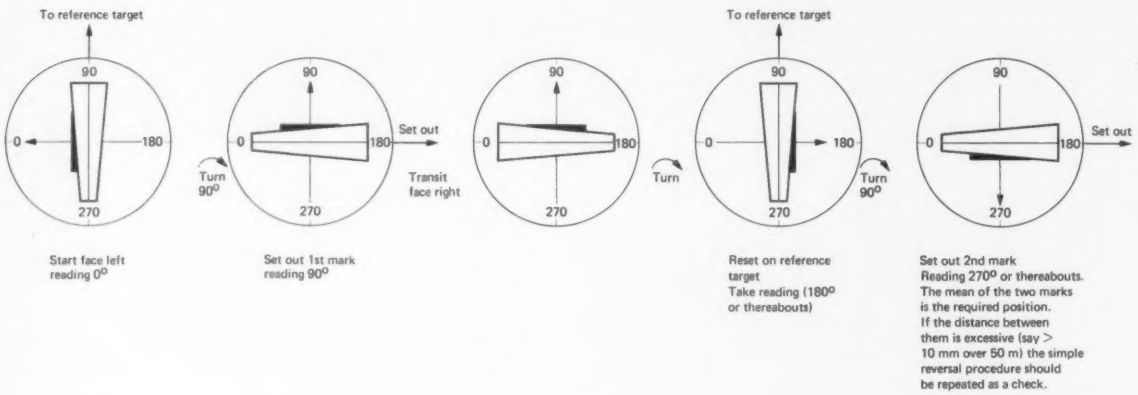

Fig 8 Setting out a right-angle using the 'simple reversal' technique

The surveyor's level

There are three types of surveyor's level currently in use on building sites: the dumpy, the tilting and the automatic level. The essential difference between them is the mechanism by which each instrument is accurately set level.

The dumpy level has a bubble tube fixed to the telescope and the line of sight is pre-set parallel to the bubble tube axis. At the start of levelling operations, the bubble is centred by adjusting the footscrews until no movement is observed when the telescope is rotated in the horizontal plane. Any number of staff readings can then be taken without any further adjustment for level.

The tilting level has a telescope hinged near its centre which can be tilted in a vertical plane. A bubble tube is rigidly attached to the telescope and pre-set so that when the bubble is brought to the centre of its run by adjusting the tilting screw, the line of sight is horizontal. At the start of the levelling process the instrument is set approximately level by reference to a circular bubble and the tubular bubble is centred immediately before each staff reading is taken.

The automatic level incorporates a pendulum mechanism which sets the sightline horizontal once the instrument has been set approximately level by reference to a circular bubble and no further fine adjustment for level is necessary. Surveyor's levels are divided into three broad classes of accuracy: builder's, engineer's and precise. Only the builder's and engineer's levels are normally used on a building site, the former being designed for levelling over comparatively short distances and having a typical accuracy specification of $\pm$ 1–1$\frac{1}{2}$ mm for a single sight over a distance of 30 m. Engineer's levels are more accurate and may confidently be used to transfer levels over longer distances. The accuracy specification for an engineer's level normally refers to a standard deviation of between 2 mm and 4 mm when double levelling over a distance of 1 km.

The attention to be given to the mechanical condition of the surveyor's level and tripod is similar to that for the theodolite and tripod

The face of levelling staves should be clean to ensure good legibility and the locating mechanism between sections should engage firmly. When a staff first arrives on site, the accuracy of graduations and, in particular, the continuity between extended sections should be checked over the full length with a steel tape.

Permanent adjustments

There are two permanent adjustments to be checked on the dumpy level: the bubble tube axis must first be set perpendicular to the vertical axis and the line of sight must then be set parallel to the bubble tube axis. With the tilting level, the line of sight must be horizontal when the tubular bubble is centred. With the automatic level, the line of sight must be horizontal when the instrument has been approximately levelled with the circular bubble.

Checking the permanent adjustments The methods used to check and adjust the bubble tube of a dumpy level are identical to those used to check and adjust the plate bubble of a theodolite described earlier. The bubble tube of a dumpy level should be checked and adjusted if necessary prior to checking the line of sight of the instrument.

Standard procedures for checking the line of sight of a surveyor's level on site are generally referred to as the 'two peg test'. This is based on the principle that the error resulting from any maladjustment is directly proportional to the distance between the staff and the instrument. A method which is commonly adopted is illustrated in Fig 9.

Select an approximately level stretch of ground and drive in two 50 mm × 50 mm timber pegs, A and B, 30 to 60 metres apart according to the operating range of the instrument, leaving their tops projecting above the ground. Set up the instrument midway between the two pegs and take readings A′ and B′ on a vertical levelling staff placed on the top of each peg in turn. The difference between these two readings is the true difference in level of the two pegs. Now set up the instrument on an extension of the line AB and as near as possible to one of the pegs (ie at minimum focusing distance, about 2–3 m) and take readings A″ and B″ on the levelling staff again placed on the top of each peg. If the difference between these readings does not equal the true difference in level of the pegs, the instrument is out of adjustment. An error of up to 1 mm in 15 metres would, for normal practical purposes, be regarded as quite satisfactory. Instruments with an error in excess of this should generally be regarded as in need of adjustment.

On sites with construction periods of many years, it is advisable to establish a permanent test-bed. Staff positions may, for example, each consist of a piece of steel reinforcement cast in vertically and protruding just above the top of a concrete block with minimum plan dimensions of 300 mm founded at such a depth that it is unlikely to suffer damage or movement.

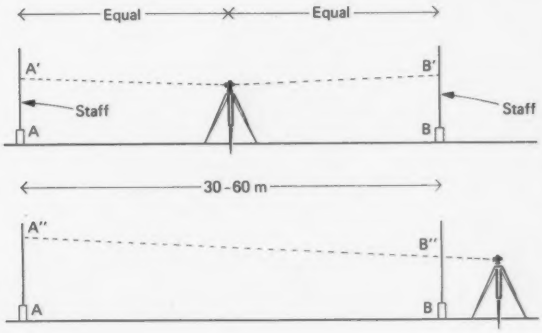

Fig 9 Checking level

Adjustment procedures

Adjustment procedures vary from instrument to instrument and the manufacturer's literature should always be consulted before undertaking any adjustments on site. Adjustment to some instruments, and in particular the dumpy and many automatic levels, involves moving the diaphragm carrying the cross-hairs; this should normally be carried out professionally. Adjustment to tilting levels involves the adjustment of the bubble tube setting screw and may be carried out on site using the following procedure.

With the instrument remaining in position close to peg B at the completion of the two peg test, first calculate the true horizontal reading on a staff vertically positioned on the peg A; for example:

Instrument set up midway between pegs A and B

Staff reading A′ = 1·510 m

Staff reading B′ = 1·480 m

A′–B′ = 0·030 m

ie peg A is 0·030 m *lower* than peg B

Instrument set up near peg B

Staff reading B″ = 1·390 m

The collimation error in the staff reading B″ may be regarded as insignificant because of the short distance between peg B and the instrument.

Calculated reading at A = 1·390 m + 0·030 m

= 1·420 m

Carefully position a vertical staff on top of peg A and adjust the line of sight with the tilting screw to coincide with the calculated reading. Finally, adjust the bubble tube adjustment screw to bring the bubble to the centre of its run.

The two peg test should now be repeated to check the adjustment.

The control of inaccuracy during levelling operations

The stability of the surveyor's level and tripod can influence the accuracy achieved and therefore procedures similar to those previously described to check the stability of a theodolite and tripod should be regularly adopted. The eyepiece must be correctly focused to eliminate parallax.

Whenever possible, sighting distances from any one instrument position should be kept short and equal to reduce instrumental errors. The levelling staff must be vertical when readings are taken. An integral or clamp-on staff bubble will aid this operation but if one is not available when the staff is used in open ground it should be swung backwards and forwards and the minimum reading accepted as being correct.

All site levelling operations must start and finish with a reading of the staff positioned on a bench mark to ensure that, where possible, unacceptable errors resulting from a disturbance of the equipment, staff reading errors and calculation errors are all detected and rectified. A level book must be used to book readings and to provide a permanent record. A check reading and check on the booking should automatically be made at every sighting. Where possible the height of datums which have been set out should be checked relative to points and surfaces of known height with a steel tape.

When using an automatic instrument a check should be made to ensure that the compensator mechanism is functioning correctly. One procedure which may be adopted is to tap the tripod gently while sighting the staff. The line of sight should move and then return to its original position.

Further reading

PD 6440: 1969 Accuracy in building; British Standards Institution; London

Basic metric surveying; W S Whyte: Newnes-Butterworths; Second edition 1976; £3.50

Department of the Environment **Building Research Establishment**

© *Crown copyright 1977*

Published by Her Majesty's Stationery Office and printed in England by Benham and Company Limited, Colchester.
Single Copies 10p each. Annual subscription inclusive of postage £2.25 for 12 monthly issues and new editions of earlier Digests.
Quantity rates (excluding postage) for bulk supply of any one Digest: 50 for £4.

Dmd. 587252 596 4/77 ISBN 0 11 724114 8